OFFICE OF NAVAL RESEARCH

Contract N00014-86-K-0043

TECHNICAL REPORT No. 117

Density of Electronic States in a Biased Resonant Tunneling Structure

by

L. N. Pandey, D. Sahu and Thomas F. George

Prepared for Publication

in

Applied Physics Letters

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

November 1989

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UBUFFALO/DC/89/TR-117	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Depts. Chemistry & Physics State University of New York 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Fronczak Hall, Amherst Campus Buffalo, New York 14260	7b. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-86-K-0043
8c. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) Density of Electronic States in a Biased Resonant Tunneling Structure	
12. PERSONAL AUTHOR(S) L.N. Pandey, D. Sahu and Thomas F. George	
13a. TYPE OF REPORT / 13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) November 1989 / 15. PAGE COUNT 14
16. SUPPLEMENTARY NOTATION Prepared for publication in Applied Physics Letters	

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
QUANTUM WELLS, RESONANT TUNNELING, ELECTRONIC STATES, BIASED, DENSITY, TRANSMISSION COEFFICIENT

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

We calculate the change in the density of states due to a biased resonant tunneling structure. The maximum of the density of states near resonance gets shifted towards the low-energy side compared to the unbiased case, as is the transmission coefficient, although the two need not be identical. For the case of asymmetric barrier heights, the left-right symmetry of the density states is broken when the field is non-vanishing.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. David L. Nelson	22b. TELEPHONE (Include Area Code) (202) 696-4410 / 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Applied Physics Letters, in press

Density of Electronic States in a Biased Resonant Tunneling Structure

L. N. Pandey, D. Sahu and Thomas F. George
Departments of Physics & Astronomy and Chemistry
Center for Electronic and Electro-optic Materials
239 Fronczak Hall
State University of New York at Buffalo
Buffalo, New York 14260

Abstract

We calculate the change in the density of states due to a biased resonant tunneling structure. The maximum of the density of states near resonance gets shifted towards low-energy side compared to the unbiased case, as is the transmission coefficient, although the two need not be identical. For the case of asymmetric barrier heights, the left-right symmetry of the density of states is broken when the field is non-vanishing.

PACS Nos.: 79.80+w, 73.20.Dx, 71.20.-b

In recent years scientists have become increasingly aware of the importance of resonant tunneling structures (RTSs) in electronic and opto-electronic device applications and their possible role in fundamental advances.[1-5] Therefore, many studies of static and dynamic aspects of resonant tunneling structures have been undertaken. A common static quantity of interest is the transmission coefficient T(E); a related physical quantity is the width of the resonance peak, which is inversely proportional to the lifetime of the resonant state. A second important static quantity is the density of states, a knowledge of which is essential in understanding transition probabilities, dielectric functions and absorption and luminescence characteristics.

Recently the local density of states,

$$N(E,x) = \sum_n \delta(E-E_n) \; |\psi_n(x)|^2 \quad , \tag{1}$$

in a RTS has been obtained and analyzed in various limits.[6,7] Here E_n are the energy eigenvalues of the system and ψ_n are the corresponding eigenstates. The global density of states obtained by integrating Eq. (1) following Ref. 6 would be identically zero. We therefore follow a different scheme to calculate the global density of states,[8]

$$N(E) = \sum_n \delta(E-E_n) \quad . \tag{2}$$

In a big box of size L ($L \to \infty$), the energy levels form a quasi-continuous spectrum. Introduction of a structure inside the box changes the spacing between the levels and produces a change $\Delta N(E)$ in the global density of

states, which we calculate. In the neighborhood of a resonance, the changes in the spacing of the energy levels produces a pronounced change in density of states. If the resonances are sufficiently narrow, $\Delta N(E)$ and $T(E)$ coincide; however, for broad resonances this is not true.

For the sake of completeness, we briefly review our method for obtaining the density of states $\Delta N(E)$ for an unbiased RTS.[8] For a flat box extending from $x = 0$ to $x = L$, the density of states in k-space is $N_o(k) = L/\pi$, where $E = \hbar^2k^2/(2m^*)$ is the energy and m^* the effective mass. Suppose now that the RTS is placed in the middle of the box, at $x = x_1 = L/2$, thereby squeezing more states into some energy region and depleting states in some other region. Suppose that the energy eigenvalues of the system are obtained from the condition $D(k) = 0$ where $D(k)$ is a determinental function of the solutions to the Schrödinger equation (see Eq. (9) below). The change in density of states associated with the n-th level having spacing Δk_n is

$$\Delta N(k_n) = \left(\frac{1}{\Delta k_n} - \frac{L}{\pi}\right) . \qquad (3)$$

The spacing Δk_n is easily obtained by finding the roots of the eigenvalue condition $D(k) = 0$ with the use of a Newton-Raphson method or any other appropriate scheme. As the previous work in our group emphasized,[8] the shifts of the energy levels depend sensitively on the phase of the wave function at the position where the structure is introduced (i.e., at $x_1 = L/2$ in this case). This phase dependence produces apparently irregular spacings of the levels, and one has to calculate two "sub-densities" (since the RTS is in the middle) in the manner indicated above and add the two to obtain the total density. As expected, for a biased RTS, calculation of $\Delta N(k)$ and hence $\Delta N(E)$

is more complicated, and the phase of the wave function in the neighborhood of the structure has to be constantly adjusted (by changing the position x_1 to $x_1'(E)$) to get the sub-densities correctly. The position x_1' at which the biased RTS should be placed is obtained from the relation

$$k'x_1' = kx_1 \quad , \tag{4}$$

where $k = (2m^*E/\hbar^2)^{\frac{1}{2}}$, $x_1 = L/2$ and $k' = [2m^*(E+V_o)/\hbar^2]^{\frac{1}{2}}$. Here V_o is the potential drop across the double barrier structure and is taken to be 10 meV throughout this work.

In Fig. 1 we show the geometry of the device. The RTS has an extension $x_3 = a_1 + a_2 + d$, where a_1 and a_2 are the barrier widths and d is the well width. The barrier heights are taken to be V_1 and V_2. The electric field in the structure is uniform and is $F = V_o/x_3$. The electric potential at any point x inside the structure is

$$V_F(x) = V_o(x_1-x)/x_3 \quad . \tag{5}$$

We label the regions of piecewise continuous potential profiles by integers, from 0 to 4, as indicated in the figure, and solve the stationary-state Schrödinger equation for the envelope function in the effective mass approximation where we assume, for simplicity, the same $m^* = 0.067\ m_e$ (m_e - electron mass) throughout the structure. In region 1, for example, the Schrödinger equation is

$$d^2\psi/dx^2 - (2m^*/\hbar^2)[V_F(x) + (V_1-E)]\ \psi(x) = 0 \quad . \tag{6}$$

This can be reduced to

$$d^2\psi(\rho)/d\rho^2 - \rho\psi(\rho) = 0 \quad , \tag{7}$$

whose solutions are the Airy functions, $A_i[\rho(x)]$, and the complementary Airy functions $B_i[\rho(x)]$,

$$\psi(\rho) = A_1 A_i(\rho) + B_1 B_i(\rho) \quad , \tag{8}$$

where A_1 and B_1 are two arbitrary constants, $\rho(x) = \alpha[(x_1-x) + (V_1-E)x_3/V_o]$ and $\alpha = [2m^*V_o/(\hbar^2 x_3)]^{1/3}$. The solutions in all the five regions can be obtained in a similar fashion. The eigenvalue condition is the condition of the vanishing of the wave function at $x = L$, so that

$$D(k) = A_4 \sin k'(L-x_2) + B_4 \cos k'(L-x_2) = 0 \quad , \tag{9}$$

where $x_2 = x_1 + x_3$, and A_4 and B_4 are obtained by demanding the usual continuity of the wave function and its first derivative with respect to x across the interfaces:

$$[A_4 \; B_4]^t = \hat{M} \; [\sin kx_1 \quad k\cos kx_1]^t \tag{10}$$

The 2 x 2 matrix $\hat{M}$ in the equation above is

$$\hat{M} = \hat{M}_{34}^{-1}(R)\hat{M}_{34}(L)\hat{M}_{23}^{-1}(R)\hat{M}_{23}(L)\hat{M}_{12}^{-1}(R)\hat{M}_{12}(L)\hat{M}_{01}^{-1}(R) \quad . \tag{11}$$

The subscripts on the matrices indicate the two regions they connect, and L and R stand, respectively, for the left and right sides of the interface.

Equations (3), (4), (10) and (11) enable us to obtain $\Delta N(E)$ for a biased RTS, which can then be compared with the transmission coefficient T(E) obtained in the usual way. We call the structure shown in Fig. 1 as a tilted box with a structure (TBWS). We define a background potential profile called the tilted box (TB) for which $V_1 = V_2 = 0$ in Fig. 1. The difference in density of states between TBWS and TB gives $\Delta N(E)$, which can be compared directly with T(E).

Figures 2-4 show T(E) and $\Delta N(E)$ for a double barrier device of barrier widths 50 Å each and heights 200 meV each, and a well width of 100 Å. Figures 2 and 3 show T(E) and $\Delta N(E)$ for the first two bound state resonances, whereas Fig. 4 is for energies above the barrier energy. A comparison with the unbiased case shows that both $T(E)$ and $\Delta N(E)$ get shifted to lower energies than the corresponding unbiased case.

For the sake of completeness, we comment on the physical origin of the energy shift of transmission resonances due to the electric field. The electron resonance energy is a compromise between the increased kinetic energy due to a spatially-varying potential and the lowering of the potential energy brought about by the field. The electron wave function wiggles a lot to accommodate the increased kinetic energy and lowers its total energy. The electron resonance energy decreases linearly for both the ground state and the first excited state for the electric field considered by us. The magnitude of the rate of decrease with the field is larger for the ground state than the first excited state.

Finally, in Fig. 5 we show our results for an asymmetric double barrier structure without a field ($V_o = 0$) and with a field ($V_o = 10$ meV). The dot-dashed curves in Fig. (7a) and (7c) represent the field-free case, and these have left-right symmetry with respect to the interchange of the two barriers. In the presence of a field, this symmetry is broken. The dashed lines correspond to the case $V_1 = 100$ meV and $V_2 = 200$ meV, whereas the dotted line corresponds to the permuted case $V_1 = 200$ meV and $V_2 = 100$ meV. This asymmetry is important in calculating tunneling currents and transition probabilities.

Acknowledgments

This research was supported by the Office of Naval Research, the National Science Foundation under Grant CHE-8620274 and the Air Force Office of Scientific Research (AFSC), United States Air Force, under Contract F49620-86-C-0009.

References

1. L. L. Change, L. Esaki and R. Tsu, Appl. Phys. Lett. 24, 593 (1974).

2. B. Ricco and M. Ya. Azbel, Phys. Rev. B 29, 1970 (1984).

3. E. H. Hauge, J. P. Falck and T. A. Fjeldly, Phys. Rev. B 36, 4203 (1987).

4. T. C. L. G. Sollner, W. D. Goodhue, P. E. Tannewold, C. D. Parker and D. D. Peck, Appl. Phys. Lett. 43, 588 (1983).

5. F. Capasso, S. Sen, A. Y. Cho and D. L. Sivco, Appl. Phys. Lett. 53, 1056 (1988).

6. T. B. Bahder, J. D. Bruno, R. G. Hay and C. A. Morrison, Phys. Rev. B 37, 6256 (1988); J. D. Bruno and T. B. Bahder, Phys. Rev. B 39, 3659 (1989).

7. G. Kim and G. B. Arnold, Phys. Rev. B 38, 3252 (1988).

8. W. Trzeciakowski, D. Sahu and T. F. George, Phys. Rev. B 40, 6058 (1989).

Figure Captions

1. metry of the tilted box with a structure (TBWS). The box extends from $x = 0$ to $x = L$ (we take L to be of the order of 1.5×10^6 Å to 1.0×10^6 Å in this work) whereas the structure extends from $x = x_1$ to $x = x_1 + x_3$, where $x_3 = a_1 + a_2 + d$. The external electric field is $F = V_o/x_3$. We take $V_o = 10$ meV throughout this paper. The zero of the energy for this and the following figures (Figs. 2-5) is taken to be the bottom of the left-most part of the box.

2. Transmission coefficient T(E) and density of states $\Delta N(E)$ for a symmetric double barrier structure (DBS) in an applied electric field. The barriers are each 50 Å wide and 200 meV high, and the well is 100 Å wide. The energy range shown is in the neighborhood of the first resonance energy. The middle panel shows $\Delta N(E)$ for a tilted box (TB), (solid curve) and a TBWS (dashed curve).

3. T(E) and $\Delta N(E)$ as in Fig. 2, but for the second resonant state.

4. T(E) and $\Delta N(E)$ as in Fig. 2, but for the energies above the barrier energy.

5. Transmission coefficient T(E) and density of states $\Delta N(E)$ for an asymmetric DBS. The barriers and the well are each 50 Å wide, and the barrier heights are 100 meV and 200 meV. The dash-dotted curves show T(E) and $\Delta N(E)$ without the field, and these curves exhibit left and right degeneracies. The dotted curves are for $V_1 = 200$ meV and $V_2 = 100$ meV, whereas the dashed curves are for $V_1 = 100$ meV and $V_2 = 200$ meV. The solid curve in the middle panel is for a tilted box, as explained in the caption to Fig. 2.

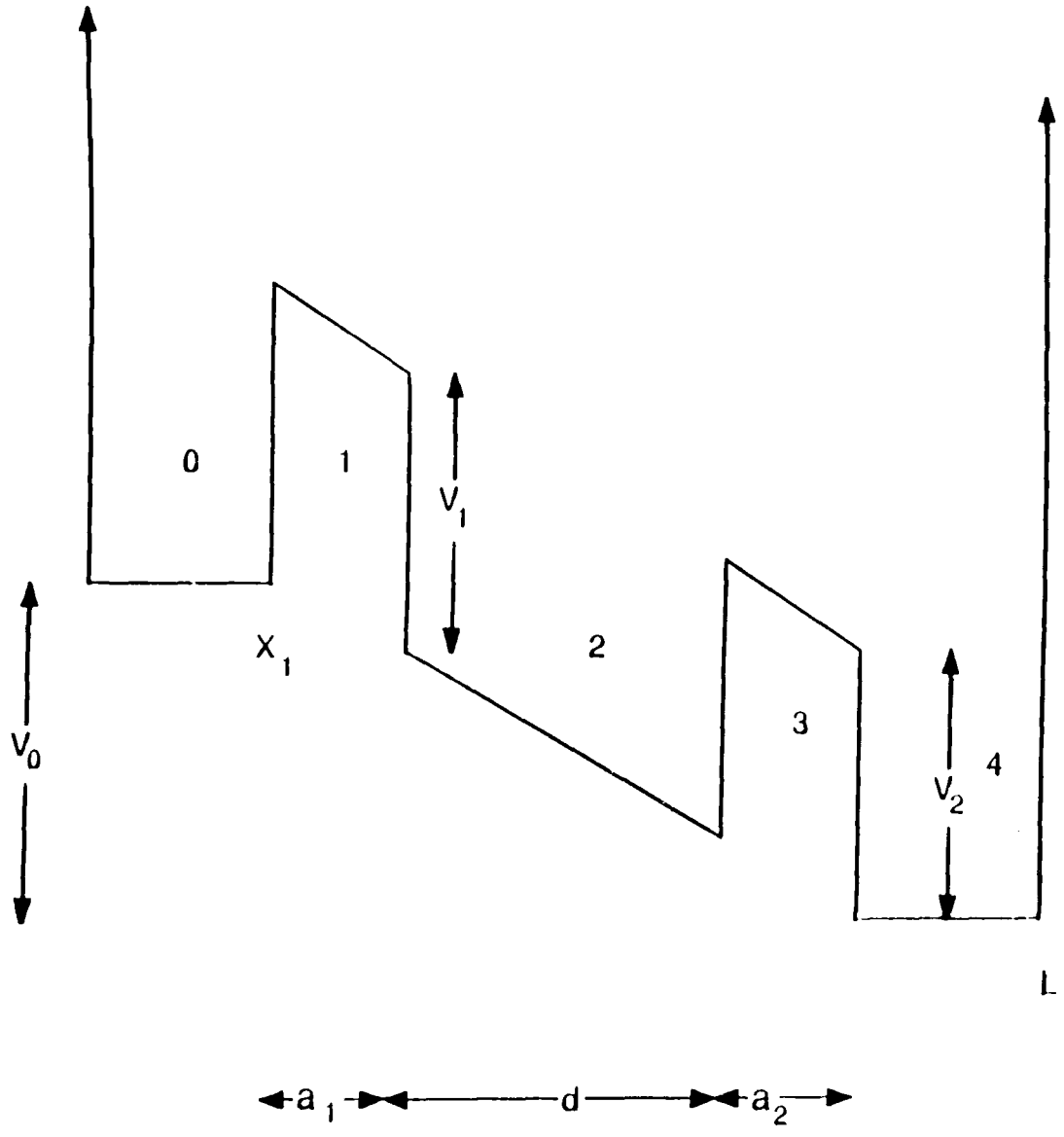


Fig. 1

Fig. 2

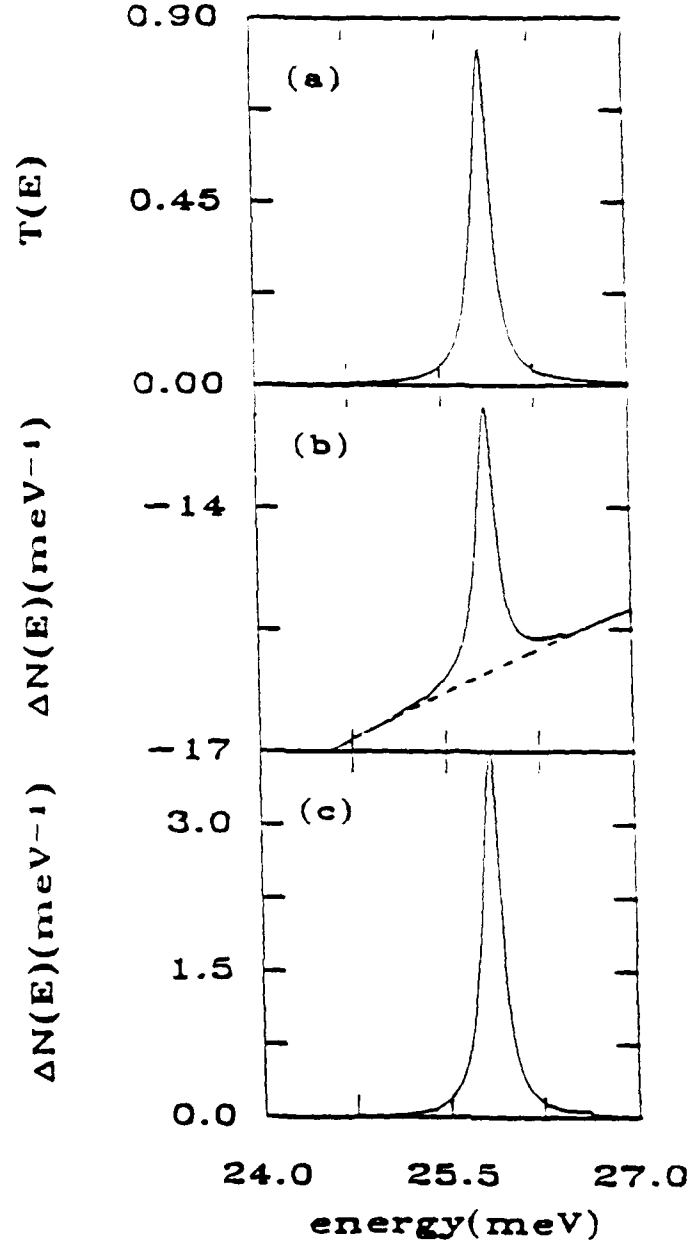

0.90
0.45
0.00
T(E)
(a)
(b)
(c)
−14
−17
ΔN(E)(meV⁻¹)
3.0
1.5
0.0
ΔN(E)(meV⁻¹)
24.0
25.5
27.0
energy(meV)

Fig. 3

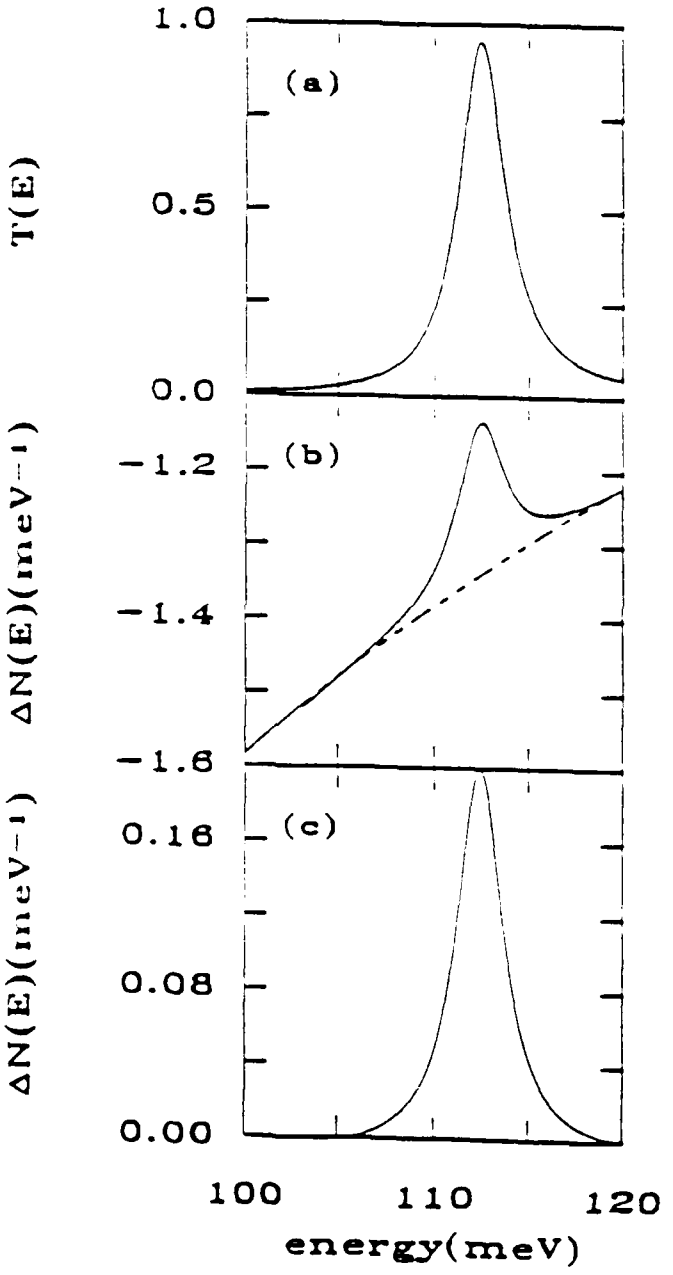

1.0
0.5
0.0
T(E)
(a)
−1.2
−1.4
−1.6
ΔN(E)(meV⁻¹)
(b)
0.16
0.08
0.00
ΔN(E)(meV⁻¹)
(c)
100
110
120
energy(meV)

Fig. 4

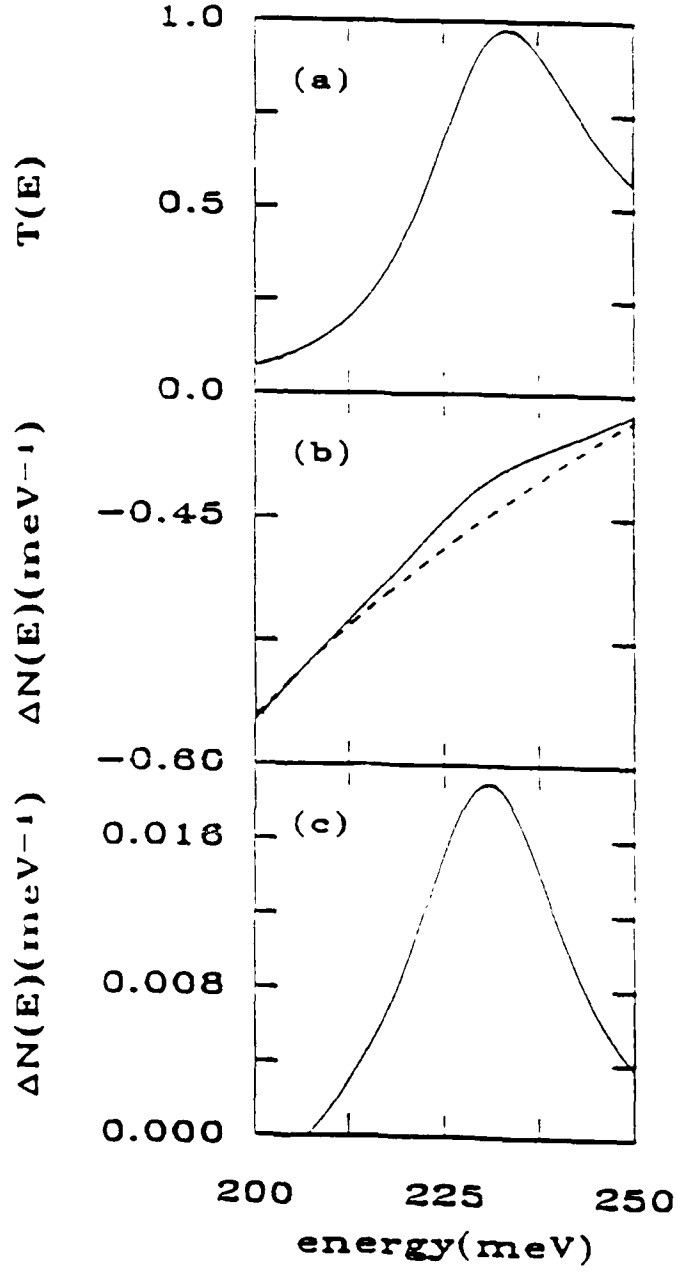
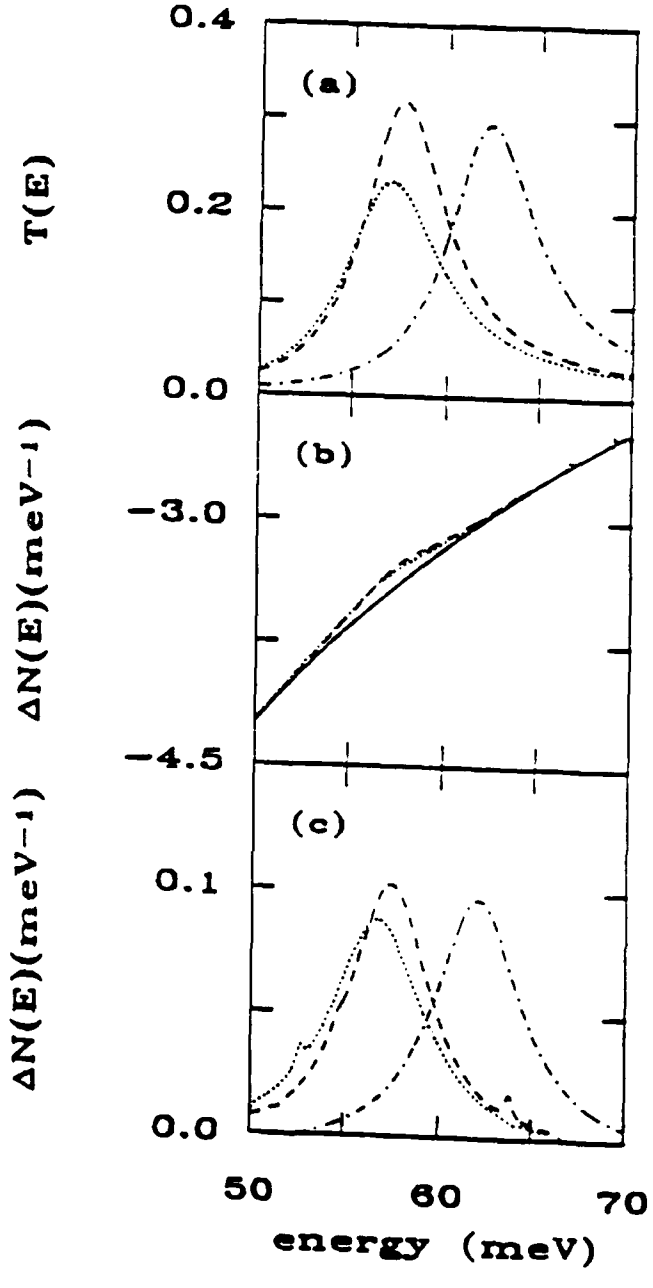

1.0
0.5
0.0
T(E)
(a)
(b)
−0.45
−0.60
ΔN(E)(meV⁻¹)
(c)
0.016
0.008
0.000
ΔN(E)(meV⁻¹)
200
225
250
energy(meV)

Fig. 5



TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies
Office of Naval Research Attn: Code 1113 800 N. Quincy Street Arlington, Virginia 22217-5000	2
Dr. Bernard Douda Naval Weapons Support Center Code 50C Crane, Indiana 47522-5050	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko, Code L52 Port Hueneme, California 93401	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12 high quality
DTNSRDC Attn: Dr. H. Singerman Applied Chemistry Division Annapolis, Maryland 21401	1
Dr. William Tolles Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375-5000	1
Dr. David Young Code 334 NORDA NSTL, Mississippi 39529	1
Naval Weapons Center Attn: Dr. Ron Atkins Chemistry Division China Lake, California 93555	1
Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1
Dr. David L. Nelson Chemistry Division Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217	1

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. J. E. Jensen
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. J. H. Weaver
Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minnesota 55455

Dr. A. Reisman
Microelectronics Center of North Carolina
Research Triangle Park, North Carolina
27709

Dr. M. Grunze
Laboratory for Surface Science and
Technology
University of Maine
Orono, Maine 04469

Dr. J. Butler
Naval Research Laboratory
Code 6115
Washington D.C. 20375-5000

Dr. L. Interante
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Irvin Heard
Chemistry and Physics Department
Lincoln University
Lincoln University, Pennsylvania 19352

Dr. K.J. Klaubunde
Department of Chemistry
Kansas State University
Manhattan, Kansas 66506

Dr. C. B. Harris
Department of Chemistry
University of California
Berkeley, California 94720

Dr. F. Kutzler
Department of Chemistry
Box 5055
Tennessee Technological University
Cookesville, Tennessee 38501

Dr. D. DiLella
Chemistry Department
George Washington University
Washington D.C. 20052

Dr. R. Reeves
Chemistry Department
Renssaeler Polytechnic Institute
Troy, New York 12181

Dr. Steven M. George
Stanford University
Department of Chemistry
Stanford, CA 94305

Dr. Mark Johnson
Yale University
Department of Chemistry
New Haven, CT 06511-8118

Dr. W. Knauer
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. G. A. Somorjai
Department of Chemistry
University of California
Berkeley, California 94720

Dr. J. Murday
Naval Research Laboratory
Code 6170
Washington, D.C. 20375-5000

Dr. J. B. Hudson
Materials Division
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Theodore E. Madey
Surface Chemistry Section
Department of Commerce
National Bureau of Standards
Washington, D.C. 20234

Dr. J. E. Demuth
IBM Corporation
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. M. G. Lagally
Department of Metallurgical
and Mining Engineering
University of Wisconsin
Madison, Wisconsin 53706

Dr. R. P. Van Duyne
Chemistry Department
Northwestern University
Evanston, Illinois 60637

Dr. J. M. White
Department of Chemistry
University of Texas
Austin, Texas 78712

Dr. D. E. Harrison
Department of Physics
Naval Postgraduate School
Monterey, California 93940

Dr. R. L. Park
Director, Center of Materials
Research
University of Maryland
College Park, Maryland 20742

Dr. W. T. Peria
Electrical Engineering Department
University of Minnesota
Minneapolis, Minnesota 55455

Dr. Keith H. Johnson
Department of Metallurgy and
Materials Science
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dr. S. Sibener
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Arnold Green
Quantum Surface Dynamics Branch
Code 3817
Naval Weapons Center
China Lake, California 93555

Dr. A. Wold
Department of Chemistry
Brown University
Providence, Rhode Island 02912

Dr. S. L. Bernasek
Department of Chemistry
Princeton University
Princeton, New Jersey 08544

Dr. W. Kohn
Department of Physics
University of California, San Diego
La Jolla, California 92037

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. F. Carter
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Richard Colton
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Dan Pierce
National Bureau of Standards
Optical Physics Division
Washington, D.C. 20234

Dr. R. Stanley Williams
Department of Chemistry
University of California
Los Angeles, California 90024

Dr. R. P. Messmer
Materials Characterization Lab.
General Electric Company
Schenectady, New York 22217

Dr. Robert Gomer
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Ronald Lee
R301
Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910

Dr. Paul Schoen
Code 6190
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. John T. Yates
Department of Chemistry
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

Dr. Richard Greene
Code 5230
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. L. Kesmodel
Department of Physics
Indiana University
Bloomington, Indiana 47403

Dr. K. C. Janda
University of Pittsburg
Chemistry Building
Pittsburg, PA 15260

Dr. E. A. Irene
Department of Chemistry
University of North Carolina
Chapel Hill, North Carolina 27514

Dr. Adam Heller
Bell Laboratories
Murray Hill, New Jersey 07974

Dr. Martin Fleischmann
Department of Chemistry
University of Southampton
Southampton 509 5NH
UNITED KINGDOM

Dr. H. Tachikawa
Chemistry Department
Jackson State University
Jackson, Mississippi 39217

Dr. John W. Wilkins
Cornell University
Laboratory of Atomic and
Solid State Physics
Ithaca, New York 14853

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. R. G. Wallis
Department of Physics
University of California
Irvine, California 92664

Dr. D. Ramaker
Chemistry Department
George Washington University
Washington, D.C. 20052

Dr. J. C. Hemminger
Chemistry Department
University of California
Irvine, California 92717

Dr. T. F. George
Chemistry Department
University of Rochester
Rochester, New York 14627

Dr. G. Rubloff
IBM
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. Horia Metiu
Chemistry Department
University of California
Santa Barbara, California 93106

Dr. W. Goddard
Department of Chemistry and Chemical
Engineering
California Institute of Technology
Pasadena, California 91125

Dr. P. Hansma
Department of Physics
University of California
Santa Barbara, California 93106

Dr. J. Baldeschwieler
Department of Chemistry and
Chemical Engineering
California Institute of Technology
Pasadena, California 91125

Dr. J. T. Keiser
Department of Chemistry
University of Richmond
Richmond, Virginia 23173

Dr. R. W. Plummer
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Dr. E. Yeager
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 41106

Dr. N. Winograd
Department of Chemistry
Pennsylvania State University
University Park, Pennsylvania 16802

Dr. Roald Hoffmann
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. A. Steckl
Department of Electrical and
Systems Engineering
Rensselaer Polytechnic Institute
Troy, NewYork 12181

Dr. G.H. Morrison
Department of Chemistry
Cornell University
Ithaca, New York 14853